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NAVAL AIR WARFARE CENTER AIRCRAFT DIVISION
PATUXENT RIVER, MARYLAND

TECHNICAL REPORT

REPORT NO: NAWCADPAX/TR-2005/20

STUDY ON CADMIUM REPLACEMENT FOR HY-TUF STEEL

by

E. U. Lee
H. C. Sanders
C. Lei
M. Yu

9 March 2005

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14. ABSTRACT Zn-5Ni alloy was selected to replace Cd as a protective plating material for Hy-Tuf steel components, such as V-22 landing gear. The integrity of Zn-5Ni alloy plated Hy-Tuf steel was investigated, performing mechanical test, open circuit potential measurement, stress corrosion cracking test, and fractographic examination. Identical investigations were also conducted with bare and Cd plated Hy-Tuf steel, and the results were compared with those of Zn-5Ni alloy plated one. The overall results indicate that Zn-5Ni alloy plating is superior to Cd plating for Hy-Tuf steel.				
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SUMMARY

As a potential Cd replacement, Zn-5Ni alloy was considered for a protective plating material of Hy-Tuf steel, and its effect on the mechanical and corrosion behavior of the plated steel was investigated. Bare, Cd plated, and Zn-5Ni alloy plated Hy-Tuf steel specimens were subjected to mechanical test, open circuit potential measurement, stress corrosion cracking test, and fractographic examination. The experimental results indicate that Zn-5Ni alloy is better than Cd for the protection against corrosion fatigue and sacrificial corrosion, and it does not change the tensile property and fatigue crack growth mode of the base steel.

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INTRODUCTION

Cd plating has been used to protect steel components of aircraft, such as landing gear, lug, and fastener, against corrosion. In addition, Cd has other useful engineering properties, including natural lubricity, excellent electric conductivity, and good ductility. However, the rapid corrosion of Cd plating causes undesirable corrosion of substrate steel components. On the other hand, Cd is highly toxic, and its environmental and health hazard is a serious concern. Exposure to respirable particles/fumes of Cd and its compounds represents a significant risk factor. Cd and its compounds are not readily absorbed through skin, but they can be ingested. Inhaling Cd or its compounds can directly cause lung cancer, and it also allows the toxic metal to enter the blood stream. Once in the blood, Cd accumulates in the kidney, degrading its function. Therefore, a viable Cd replacement must be found and identified.

As a potential replacement of Cd, Zn alloys are considered. Zn alloys provide notable advantages. First, they are not toxic, and so not an environmental and health hazard. Second, electrochemically, they have different corrosion potentials from their alloying elements. Therefore, they can be designed to corrode much more slowly than Zn when exposed to a corrosive environment. The prospective alloys are Zn-Ni, Zn-Fe, Zn-Co, and Zn-Sn. Among them, Zn-Ni alloys, containing 5 to 15% Ni, are known to produce higher corrosion resistance (reference 1). However, the mechanical and metallurgical properties and resistance to corrosion-assisted cracking of the Zn-Ni alloy plated steel components have not been fully understood and remain to be established.

EXPERIMENTAL PROCEDURE

MATERIAL AND SPECIMEN

As the substrate material, a slab of Hy-Tuf steel, the material of V-22 landing gear, was used. Its chemical composition is shown in table 1.

Table 1: Chemical Composition of Hy-Tuf Steel

Element	Weight (%)
C	0.25
Mn	1.35
Si	1.50
Cr	0.30
Ni	1.80
Mo	0.40
Fe	Balance

The slab was subjected to the following heat treatment:

1. Normalization: Heating at 1700°F for 1 hr and air cooling.
2. Austenitizing and Quenching: Heating at 1600°F for 1 hr and oil quenching.
3. Tempering: Heating at 500°F for 4 hr and air cooling.

The postheat-treatment microstructure is shown in figure A-1 and the hardness was measured to be Rockwell C 47~51.

The slab was machined to round tension test specimens in L-orientation (figure A-2), round hourglass fatigue test specimens in L-orientation (figure A-3), and square bar stress corrosion cracking test specimens in L-T orientation (figure A-4). Subsequently, each of the three specimen groups was subdivided into three subgroups, two of which were plated with Cd and Zn-5Ni alloy, respectively. The Cd plating was done at NAWCAD Patuxent River, Maryland, following the National Aerospace Standard NAS 672, *Plating – High Strength Steels – Cadmium* (reference 2). The Zn-5Ni alloy plating was done at Courter-Hall Co., Garland, Texas. The plating thicknesses were 0.3 mil (0.0003 in.) for the Cd and 0.5 mil (0.0005 in.) for the Zn-5Ni alloy.

TENSION AND FATIGUE TESTS

A closed-loop servohydraulic mechanical test machine, Interlaken, of 90 KN (20 kip) capacity, was utilized for the tension and fatigue tests. The tension test was conducted with the round tension test specimen in air, following the ASTM E 8, Standard Test Methods for Tension Testing of Metallic Materials (reference 3). The tensile loading rate was 0.076 mm/min (0.003 in./min). The fatigue test was carried out with the hourglass specimen under stress control in tension-tension cycling at stress ratio 0.1 and frequency 10 Hz in air and aqueous 3.5% NaCl solution of pH 7.3. This test followed the ASTM E 466, Standard Practice for Conducting Force Controlled Constant Amplitude Axial Fatigue Tests of Metallic Materials (reference 4).

OPEN CIRCUIT POTENTIAL MEASUREMENT

Open circuit potential (OCP) is an electrochemical parameter of corrosion resistance and measurable in a corrosion cell, consisting of a specimen electrode and a reference electrode (saturated calomel electrode (SCE)) in an electrolyte. In this study, the specimen electrodes were rectangular flat sheets of Hy-Tuf steel, 38 x 7 x 1 mm, which were bare, Cd plated, and Zn-5Ni alloy plated, respectively. The surface of each specimen was coated with Stop-Off Lacquer, except an area of 5 x 7 mm on one face. This area became the working electrode in the electrolyte, aqueous 3.5% NaCl solution of pH 7.3. The specimen and reference electrodes were connected to the ground terminals of an electrometer, and the electrode potential and its change with time were recorded in reference to the SCE. The electrode potential, stabilized after a prolonged exposure period, was taken as the OCP.

STRESS CORROSION CRACKING TEST

Since the cantilever bend and double cantilever beam Stress Corrosion Cracking (SCC) tests take a long time, an accelerated SCC test (reference 5) was conducted in a RSL 1000 SI-Multi-Mode Test System. This System included a bending frame, a tensile loading frame, an electrolyte reservoir, a pump for electrolyte circulation, a saturated calomel electrode, a platinum counterelectrode, a PC, and a printer. The precracked specimen was step-loaded until the load dropped in four-point bending under constant displacement control, while held at a given potential in aqueous 3.5% NaCl solution of pH 7.3. The load drop corresponds to the threshold stress intensity for stress corrosion crack growth, K_{ISCC}. The K_{ISCC} was calculated as a function of applied bending moment and crack length, using the following equation:

$$K_{ISCC} = \sigma\sqrt{\pi a} * F(a/W)$$

where

σ: gross stress = $6M/bW^2$
M: bending moment = Px
P: applied load
x: moment arm length
b: specimen thickness
W: specimen width
a: crack length
$F(a/W) = 1.122 - 1.40\,(a/W) + 7.33(a/W)^2 - 13.08(a/W)^3 + 14.0(a/W)^4$

The K_{ISCC} value, determined at the open circuit potential, is the measure of SCC resistance under free corrosion condition.

FRACTOGRAPHY

After the fatigue test, the fracture surface morphology was examined with a scanning electron microscope, JEOL JSM-5800LV, operating at an accelerating voltage of 20 kV.

RESULTS AND DISCUSSION

TENSILE PROPERTIES

The tensile properties of the Hy-Tuf steel, bare and Zn-5Ni alloy plated, are determined to be

Property	Bare	Zn-5Ni Plated
0.2% Yield Strength MPa (ksi)	1358 (197)	1358 (197)
Ultimate Tensile Strength MPa (ksi)	1703 (247)	1703 (247)
Elongation (%)	15	15

This result indicates that the Zn-5Ni alloy plating does not change the tensile properties of Hy-Tuf steel.

FATIGUE BEHAVIOR

The stress-life (S-N) curves are shown for the bare, Cd plated, and Zn-5Ni alloy plated Hy-Tuf steel specimens, fatigue tested in air and 3.5% NaCl solution, in figures A-5 through A-9.

The fatigue life is much shorter in 3.5% NaCl solution than in air, especially at lower applied stresses, for the bare specimen, figure A-5. On the other hand, such a fatigue life reduction is slight for the Zn-5Ni alloy plated specimen and none for the Cd plated one, figures A-6 and A-7. The fatigue resistances of the bare and plated specimens in air and 3.5% NaCl solution are compared in figures A-8 and A-9, respectively. In air, the fatigue resistance is similar for the bare and Zn-5Ni alloy plated specimens, and it is inferior for the Cd plated one, figure A-8. In 3.5% NaCl solution, Zn-5Ni alloy plating can protect the Hy-Tuf steel from corrosion fatigue better than the Cd plating, especially at lower applied stresses, figure A-9.

OPEN CIRCUIT POTENTIAL

During its measurement, the potential was initially fluctuating and unstable, but eventually stabilized with time. The potential variation with time is shown for the bare, Cd plated, and Zn-5Ni alloy plated specimens in figures A-10, A-11, and A-12. The final stabilized potential was taken as the OCP. The OCP values are

Specimen	OCP (V)
Bare	-0.632
Cd Plated	-0.760
Zn-5Ni Plated	-0.887

These values suggest that the susceptibility to general corrosion is greatest for the Zn-5Ni alloy plated specimen, intermediate for the Cd plated one, and least for the bare one. Therefore, it is clear that the role of sacrificial plating can be played more by Zn-5Ni alloy plating than by the Cd plating.

STRESS CORROSION CRACKING RESISTANCE

As the measure of SCC resistance, the stress intensity for stress corrosion crack initiation from notch, bare or plated, with no precracking, K_{OSCC}, was taken. The K_{OSCC} variation with applied electric potential V_{SCE} is shown in figure A-13. This figure shows that the Zn-5Ni alloy plated specimen has the least, the Cd plated one the intermediate, and the bare one the greatest K_{OSCC} value in 3.5% NaCl solution. In other words, the SCC resistance is greatest for the bare specimen, intermediate for the Cd plated one, and least for the Zn-5Ni alloy plated one. This behavior is attributable to greater corrosion susceptibility for the sacrificial platings of Zn-5Ni alloy and Cd than for the bare Hy-Tuf steel.

SCANNING ELECTRON MICROSCOPE FRACTOGRAPH

Figures A-14, A-15, and A-16 show the Scanning Electron Microscope (SEM) fractographs of bare, Cd plated, and Zn-5Ni alloy plated specimens, which were fatigue-tested in air and 3.5% NaCl solution. Those fractographs illustrate the fracture surface morphologies of the slow crack growth area, including the vicinity of crack initiation site.

The SEM fractographic features are similar for the bare and plated specimens, fatigue-tested in air and 3.5% NaCl solution. The common features are:

- The crack initiation site is located on the specimen surface.
- Radial marks are diverging into the thickness from the crack initiation site. This evidences the crack growth into the thickness from the crack initiation site.
- Striations are observable on plateaus. This feature is typical of fatigue crack growth.

From the above common fractographic features and the aforementioned fatigue resistances, figures A-8 and A-9, it is clear that the Cd and Zn-5Ni alloy platings provide Hy-Tuf steel different resistances to corrosion fatigue but do not change the basic mode of fatigue crack growth.

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CONCLUSIONS

- Zn-5Ni alloy plating does not change the tensile properties of its substrate metal, Hy-Tuf steel.
- Zn-5Ni alloy plating provides Hy-Tuf steel better protection against corrosion fatigue in 3.5% NaCl solution than Cd plating.
- Zn-5Ni alloy plating is more susceptible to general corrosion and stress corrosion cracking than Cd plating, and so the former can play the role of sacrificial plating better than the latter.
- Zn-5Ni alloy and Cd platings do not change the mode of crack growth in the substrate metal under cyclic loading, although they affect the fatigue life in 3.5% NaCl solution.

RECOMMENDATION

It is recommended to extend this study to include an investigation of the other Zn-Ni alloy platings and identify the optimum one for Hy-Tuf steel.

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REFERENCES

1. Nabil Zaki, "Zn Alloy Plating," *ASM Handbook*, *Vol. 5, Surface Engineering*, ASM International, pp. 264-65.

2. National Aerospace Standard NAS 672, *Plating – High Strength Steels – Cadmium.*

3. ASTM E 8, "Standard Test Methods for Tension Testing of Metallic Materials," *2003 Annual Book of ASTM Standards*, Vol. 03.01.

4. ASTM E 466 - 96, "Standard Practice for Conducting Force Controlled Constant Amplitude Axial Fatigue Tests of Metallic Materials," *2003 Annual Book of ASTM Standards*, Vol. 03.01.

5. The Rising Step-Load Test, *ASM Handbook, Vol. 8, Mechanical Testing*, ASM International, June 1995, pp. 539-40.

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APPENDIX A
FIGURES

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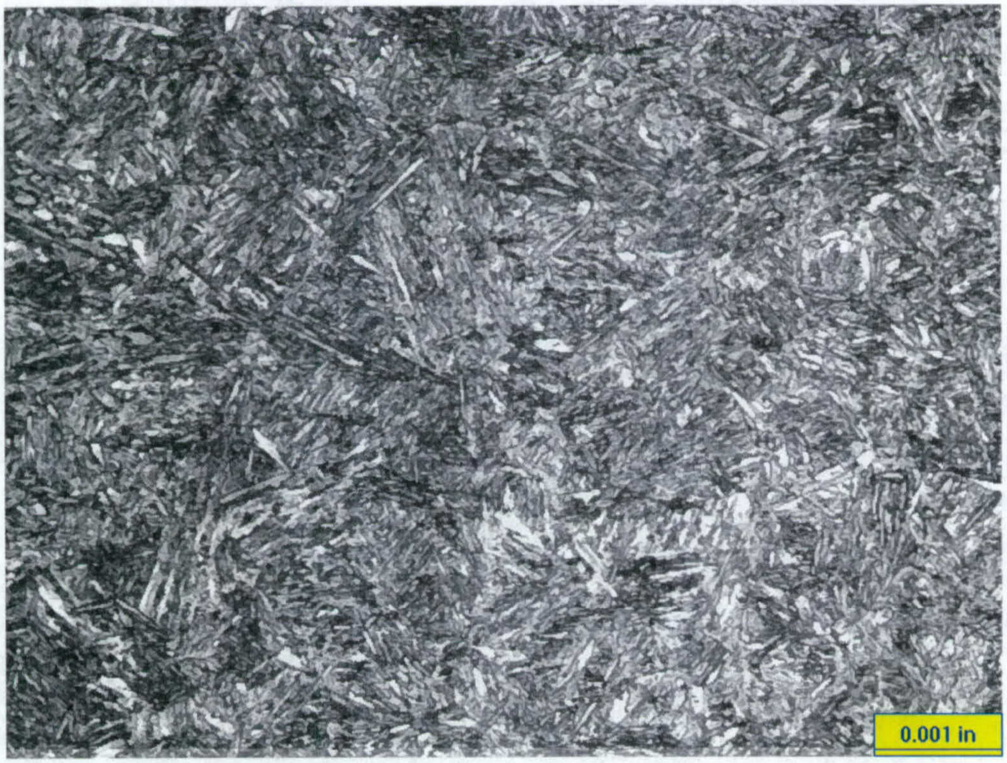


Figure A-1: Microstructure of Hy-Tuf Steel

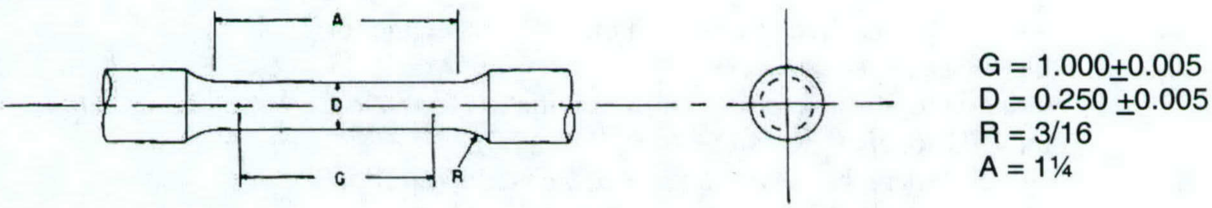


Figure A-2: Round Tension Test Specimen

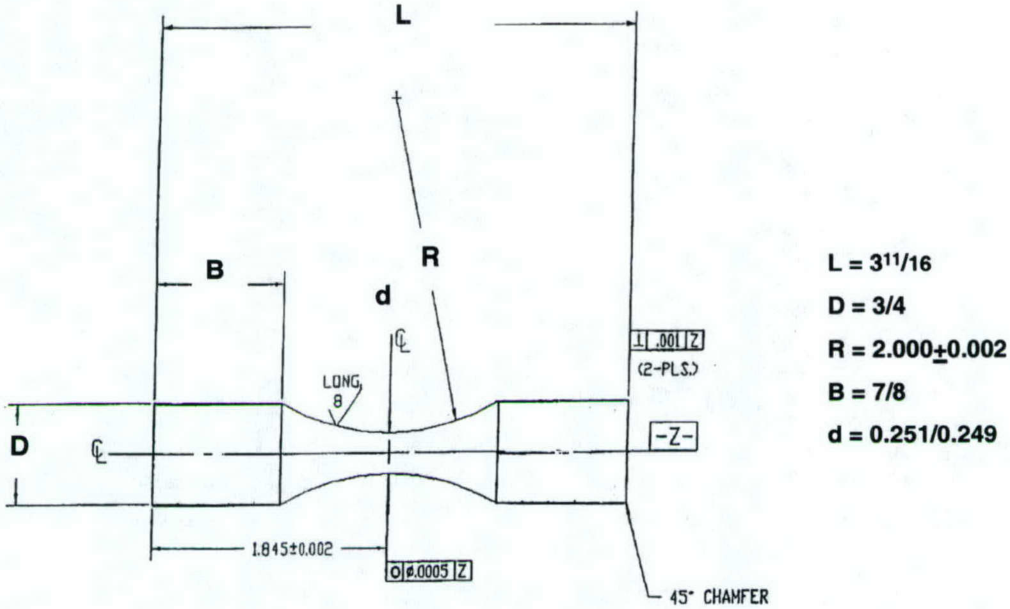


Figure A-3: Round Hourglass Fatigue Test Specimen

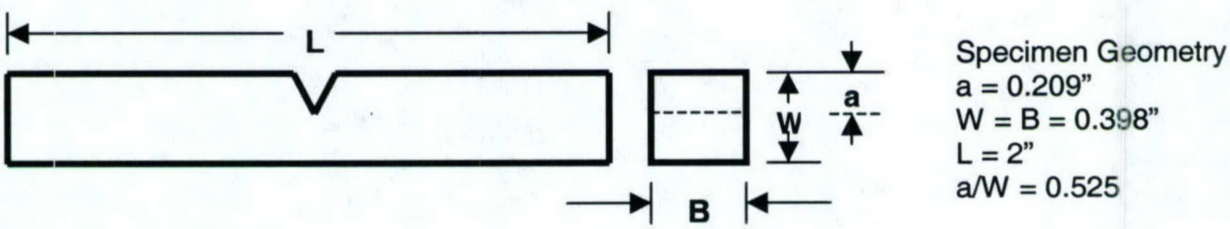


Figure A-4: Square Bar Stress Corrosion Cracking Test Specimen

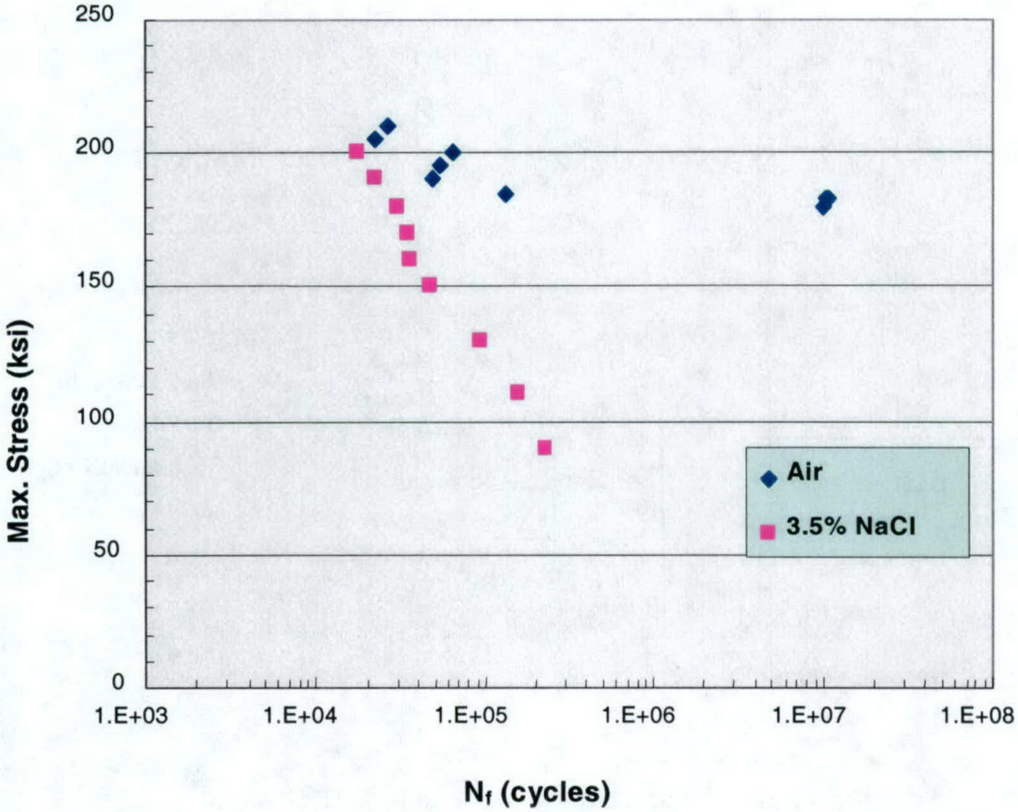


Figure A-5: Stress-Life Curves for Bare Hy-Tuf Steel in Air and 3.5% NaCl Solution

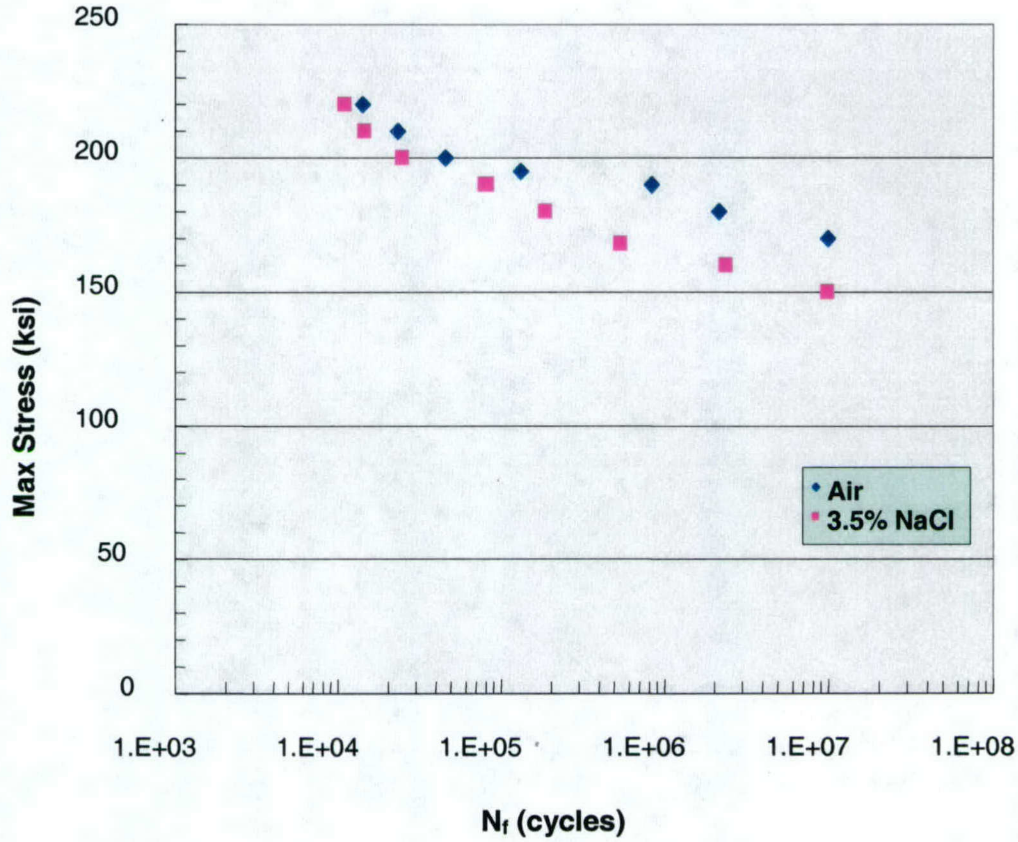


Figure A-6: Stress-Life Curves for Zn-5Ni Plated Hy-Tuf Steel in Air and 3.5% NaCl Solution

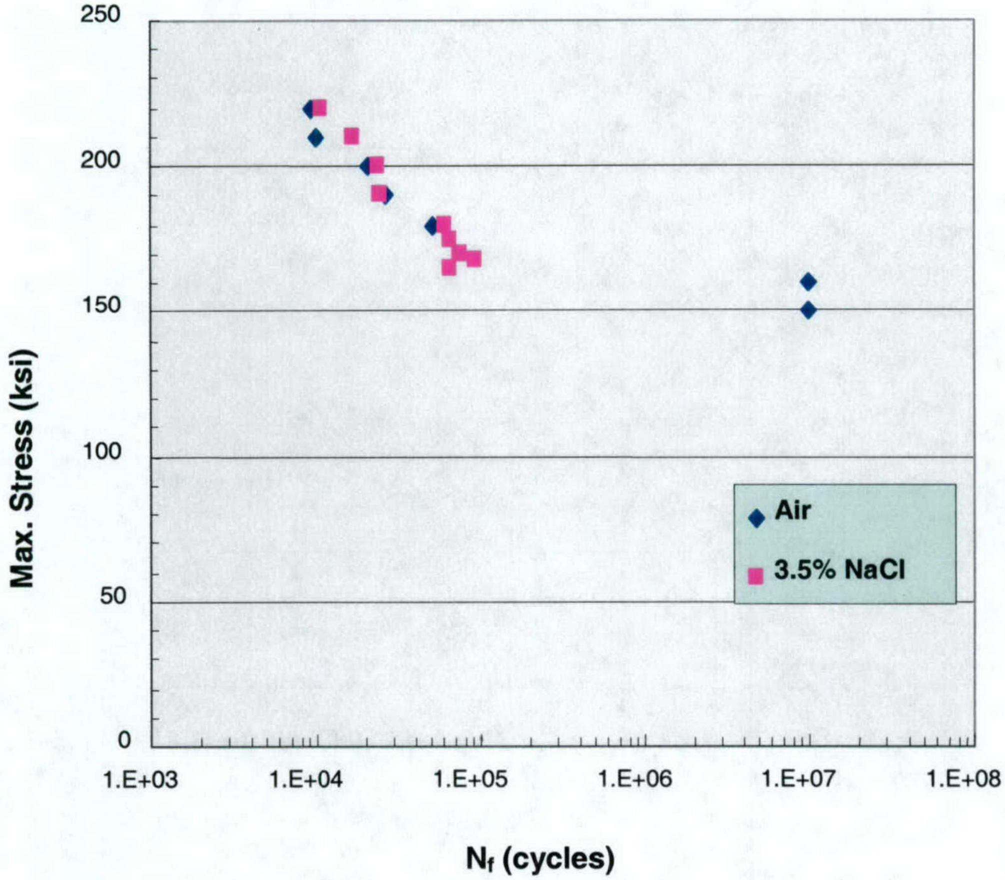


Figure A-7: Stress-Life Curves for Cd Plated Hy-Tuf Steel in Air and 3.5% NaCl Solution

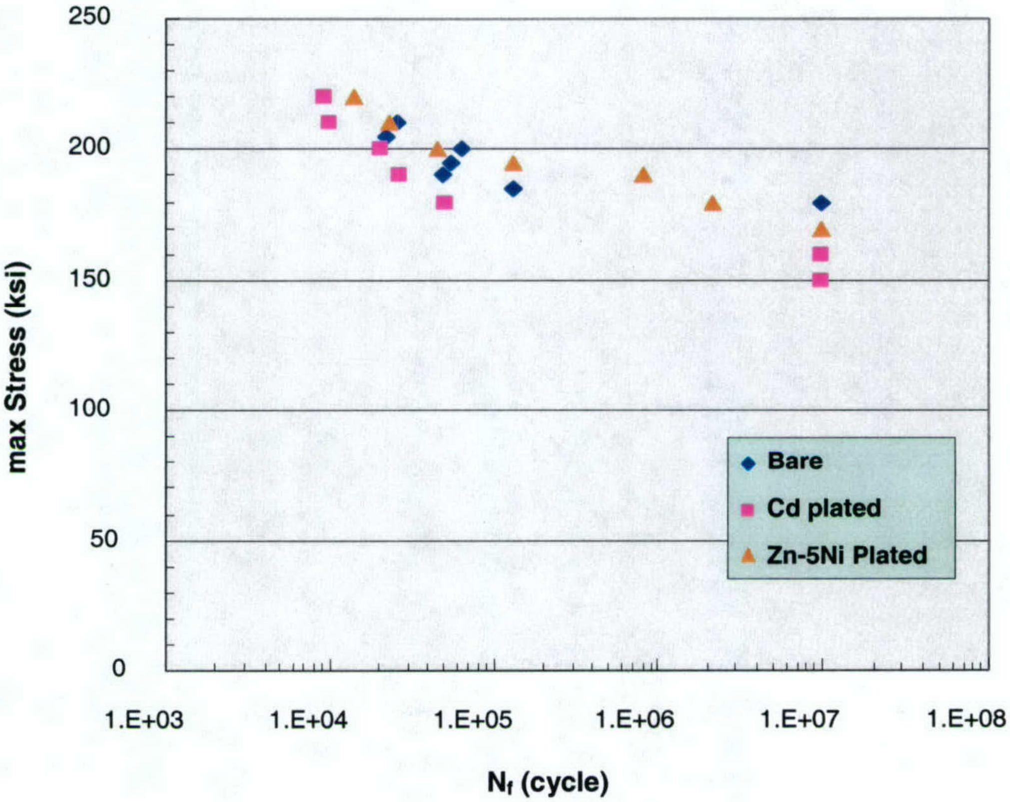


Figure A-8: Stress-Life Curves for Bare, Cd Plated, and Zn-5Ni Plated Hy-Tuf Steel in Air

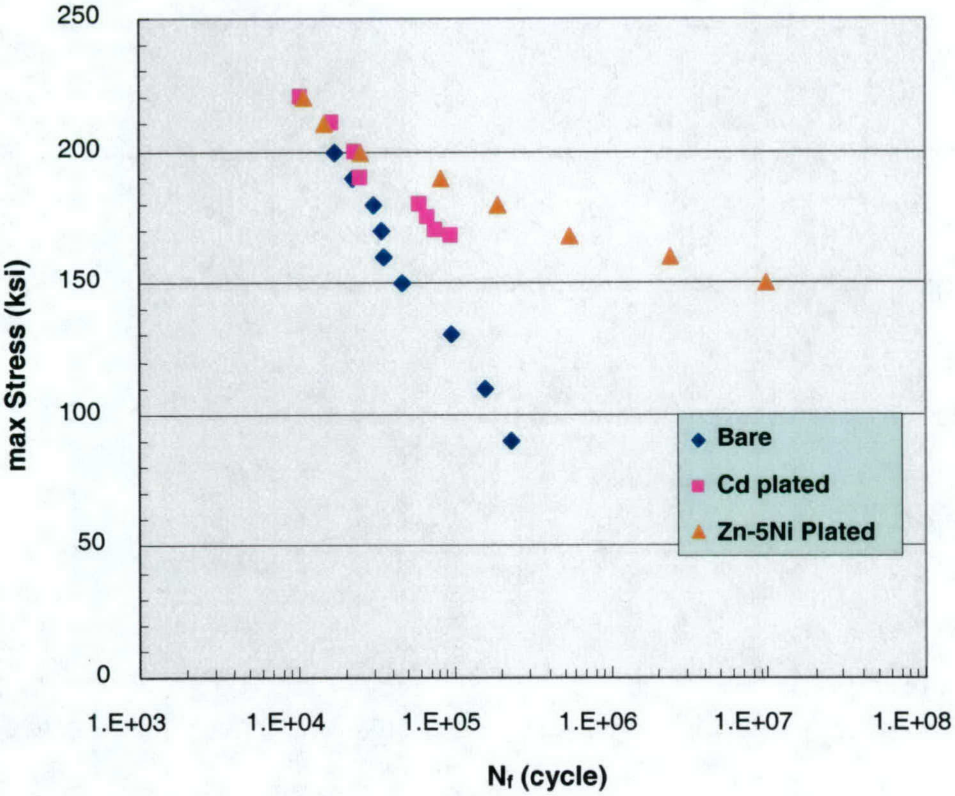


Figure A-9: Stress-Life Curves for Bare, Cd Plated, and Zn-5Ni Plated Hy-Tuf Steel in 3.5% NaCl Solution

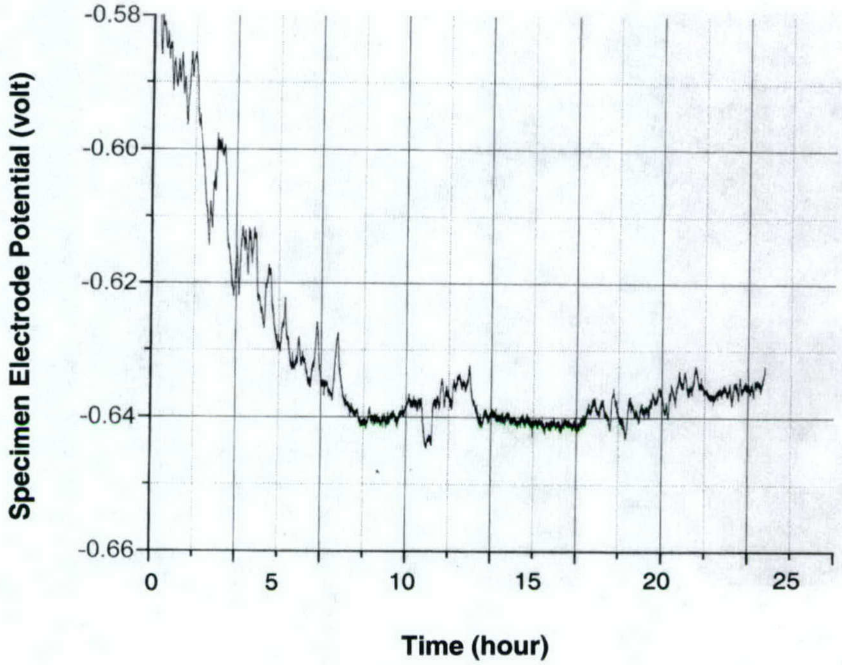


Figure A-10: Variation of Specimen Electrode Potential With Time for Bare Hy-Tuf Steel

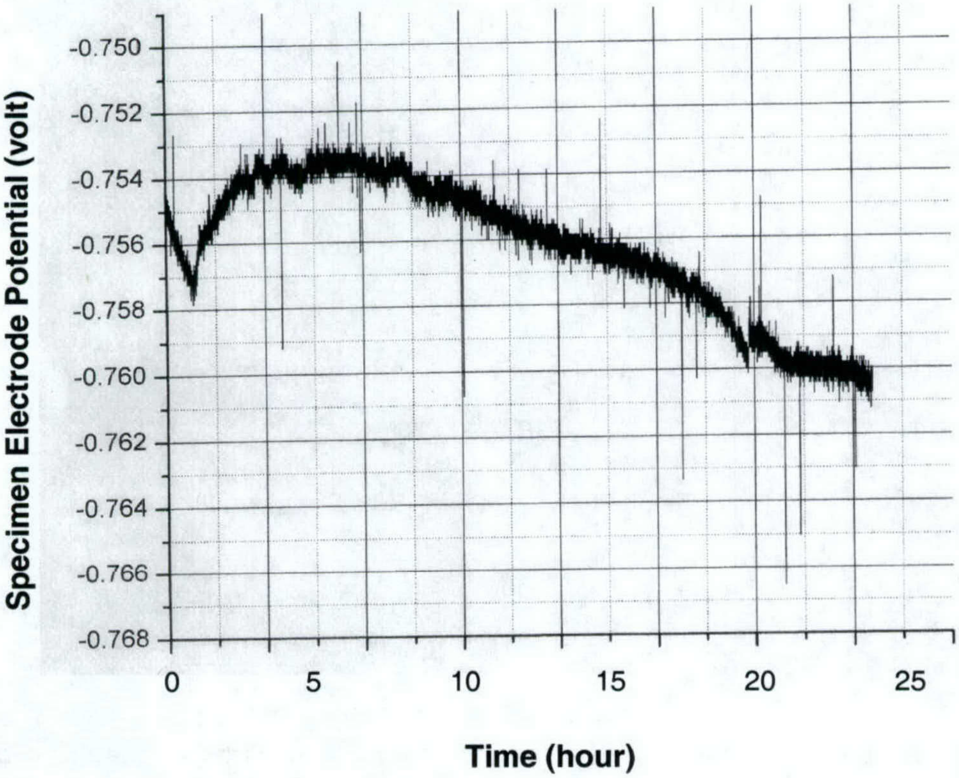


Figure A-11: Variation of Specimen Electrode Potential With Time for Cd Plated Hy-Tuf Steel

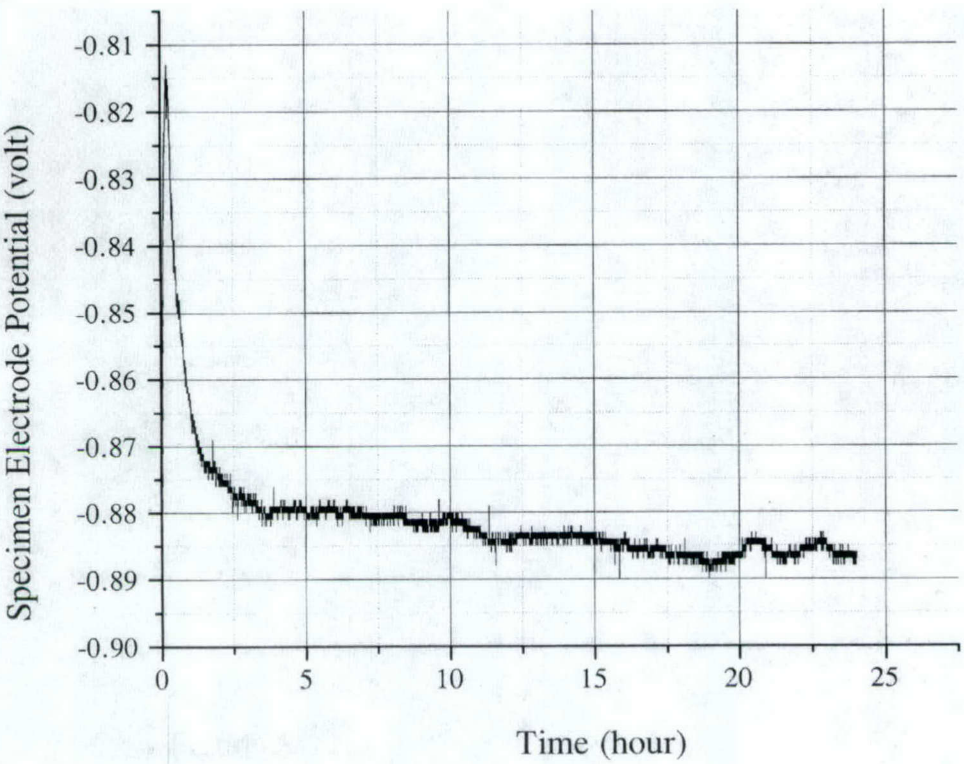


Figure A-12: Variation of Specimen Electrode Potential With Time for Zn-5Ni Alloy Plated Hy-Tuf Steel

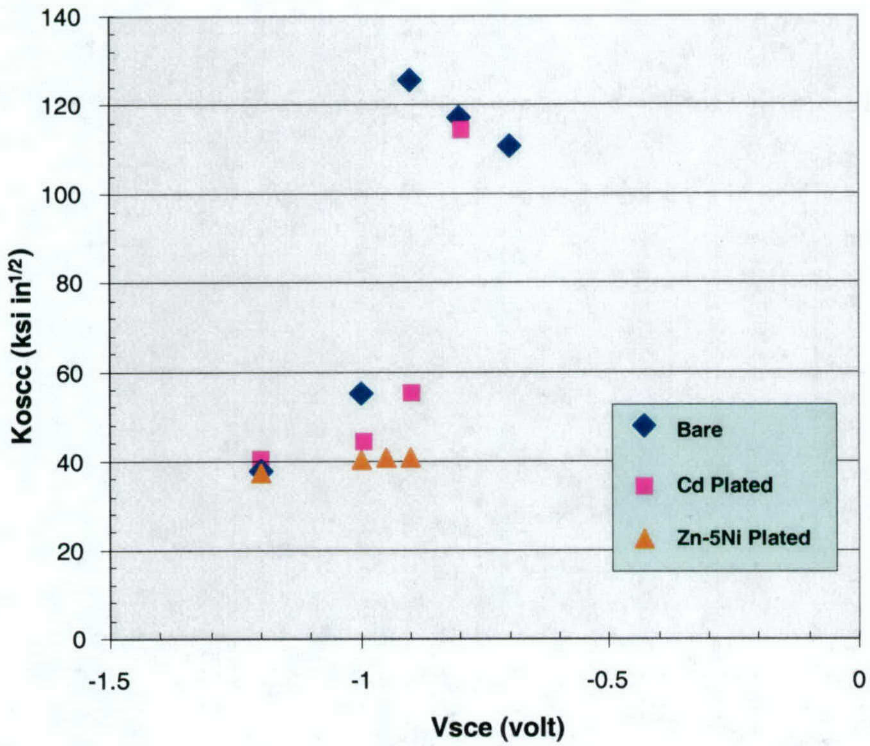
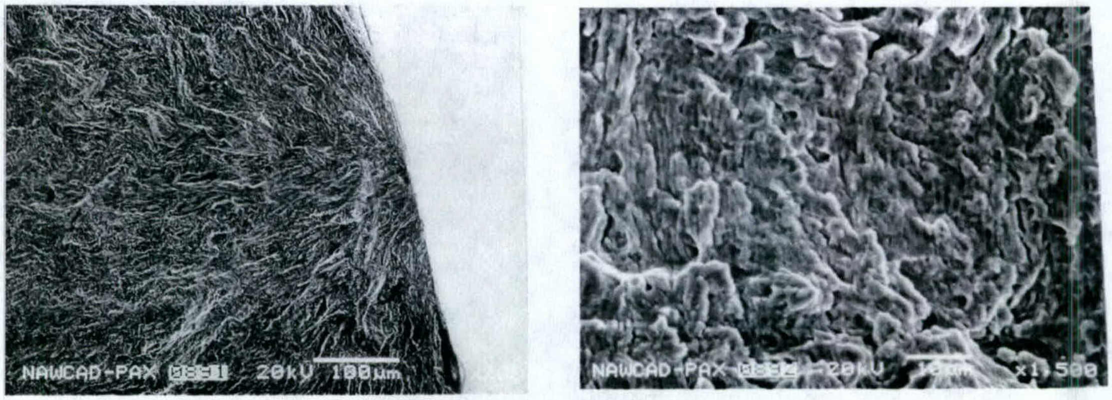
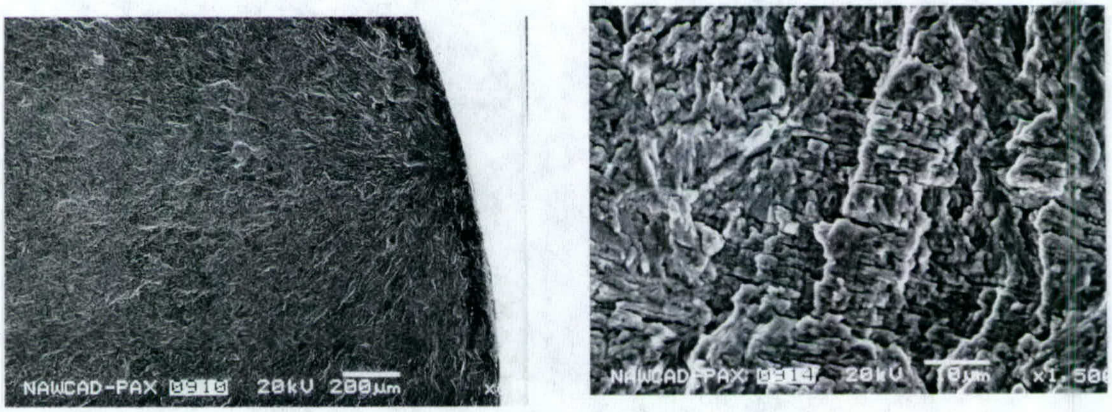


Figure A-13: Variation of Stress Intensity for SCC Initiation from Notch With Applied Electric Potential

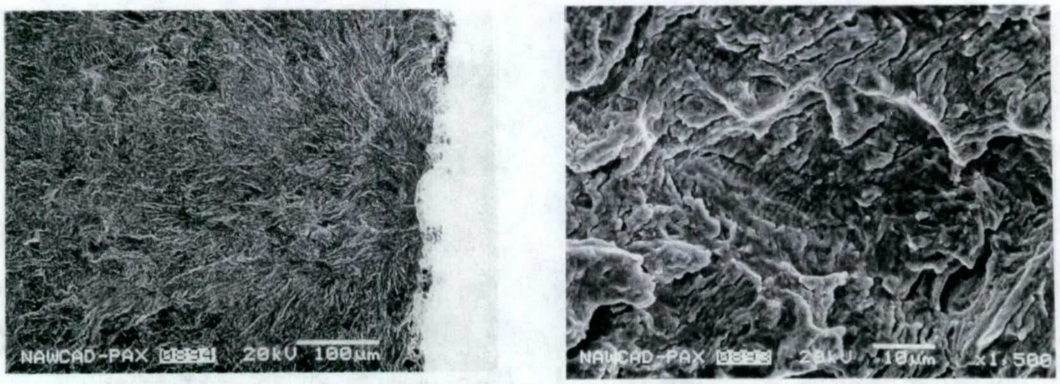


(a) Fatigue-tested in Air

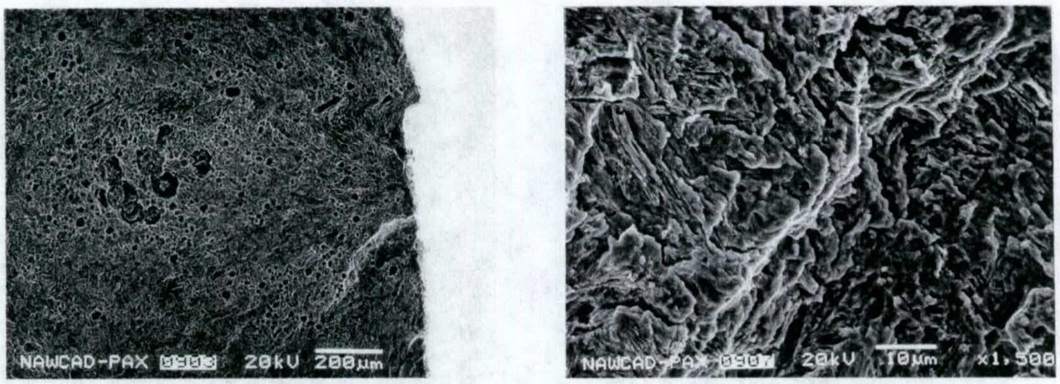


(b) Fatigue-tested in 3.5% NaCl Solution

Figure A-14: SEM Fractographs of Bare Specimens, Fatigue-Tested in Air and 3.5% NaCl Solution

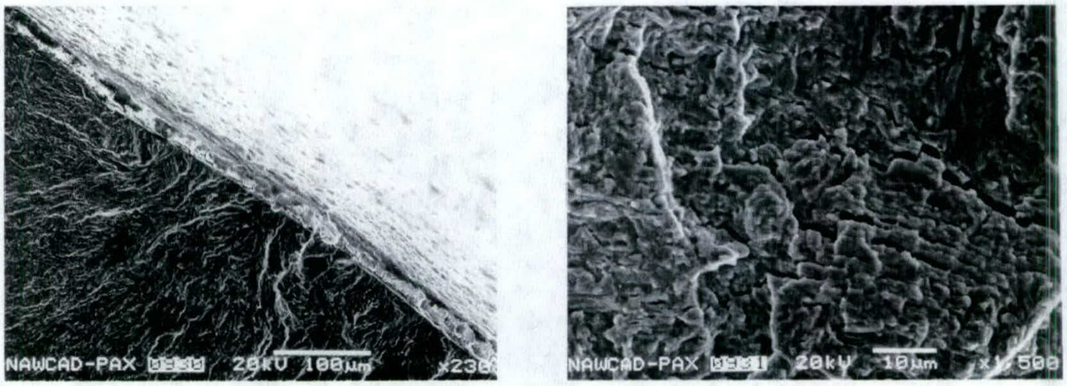


(a) Fatigue-tested in Air

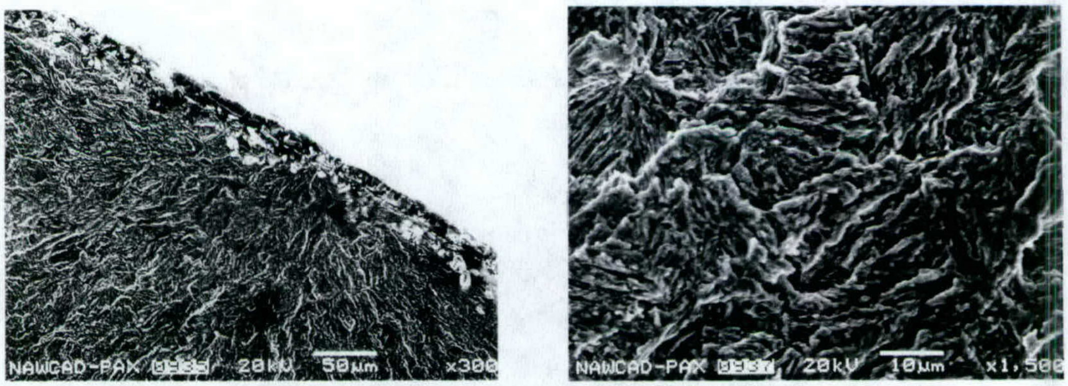


(b) Fatigue-tested in 3.5% NaCl Solution

Figure A-15: SEM Fractographs of Cd Plated Specimens, Fatigue-Tested in Air and 3.5% NaCl Solution



(a) Fatigue-tested in Air



(b) Fatigue-tested in 3.5% NaCl Solution

Figure A-16: SEM Fractographs of Zn-5Ni Alloy Plated Specimens, Fatigue-Tested in Air and 3.5% NaCl Solution

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